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OPTICAL PROPERTIES OF THE BLACK SEA: RESULTS OF THE COMSBLACK AND TU-BLACK SEA PROGRAMS

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Abstract. The results of the earlier optical studies together with the recent measurements carried out within the framework of the CoMSBlack and TU-Black Programs between 1991-1995 are given. The observations reported here are the first basin wide measurements of the optical variables in the Black Sea. Basin wide optical data set collected during July 1992 was analyzed which correspond to lowest water transparency observation among the all measurements done in the basin. Optical properties water model was applied to understand this extreme case. The long-term variability of the Black Sea water transparency found in connection with 11-year cycle of solar activity. The turbid boundary layer at the oxic/anoxic zone of the Black Sea and its connection with hydrophysical and hydrochemical factors were investigated.

1. Introduction

Since 1991 institutes from the Black Sea countries and the USA have conducted joint investigations of the Black Sea within the framework of the Cooperative Marine Science Program for the Black Sea (CoMSBlack). The basic goals of this program are to coordinate the national programs of the participant countries in research and monitoring of the sea, and to obtain essential data assessing the ecological condition of the sea. Part of this program includes joint multi-disciplinary surveys of the Black Sea throughout the entire basin. Since 1994 this research is continuing in the framework of the TU-Black Sea Program.

These surveys allow to obtain for the first time distribution of surface water transparency throughout the basin and to estimate its optical state at the time of the survey. There are two basin-wide surveys with optical measurements: in September 1991 (HydroBlack-91) and in July 1992 (CoMSBlack-92).

The present study, part of the NATO TU-Black Sea project, aims to improve our understanding of the variability of the Black Sea optical properties. In this paper we

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examine the features of the optical variability of the Black Sea throughout the measurements carried out by the Institute of Marine Sciences of Middle East Technical University (IMS) and Marine Hydrophysical Institute of Ukrainian Academy of Sciences (MHI). Section 2 presents a description of the data set and methods used and then consequent sections discuss different aspects of the Black Sea optical structure using observations and model studies. Although the present review derives largely from previous studies, further discussion has been added, based on combinations of the data sets obtained by IMS and MHI.

2. Instruments and methods

The optical data were collected during a series of cruises (Table 1) by the different institutes as part of international programs between 1991 and 1995. In this paper we use data only from IMS and MHI.

The Secchi disk measurements have been used to study long term variability of the water transparency. Secchi disk provides simple visual index of water clarity. The Secchi disk is a circular white disk of a 0.3 meter diameter that is lowered into the sea by human observer until it disappears from view. The depth of disappearance is called as a Secchi disk depth. The uniformity in the methodology used and existence of the big amount of the data since beginning of this century makes it suitable for studying long term variability of optical properties in the Black Sea.

In July 1992, the data obtained by the MHI and IMS were the first basin wide measurements and these data were suitable for studies of vertical optical structure of the Black Sea. Measurements of the Secchi disk depth cover entire basin and the measurements of the vertical profiles of attenuation coefficient were done at all the stations occupied in the EEZ of Ukraine, Russia and Turkey by IMS and MHI.

The measurements of the vertical distribution of the beam attenuation coefficient were done by MHI using sounding autocollimational transmissometers LFP and AKP. These instruments were designed and produced in MHI. The beam attenuation coefficient (c) is determined as

$$c\ [m^{-1}]=(1/L)*Log(F_L / F_0)$$

where F_0 and F_L are the light fluxes before and after traversing in the water of path L, called the optical base of a transmissometer. The results of measurements are given as m^{-1} at the decimal logarithm.

These instruments are designed as dual-beam photometers with a single photoreciever alternately irradiated with a measuring and a reference light beams. The photoreceiver is loaded with the logarithm amplifier. The output is an alternating signal proportional to the difference between the logarithms of compared radiant fluxes, i. e. to the optical density of the medium which fills the instrument measuring base. The optical base L of transmissometers LFP and AKP are equal to 1 meter. Interference filters are used to separate the narrow spectral bands from the light source. Usually, the

Table 1. Main optical measurements, performed in the Black Sea in 1991-1995

R/V, Cruise	Time, start	Time, end	Region	Trans-parency, profiles	Trans-parency, samples	Secchi disk	Irradiance
MHI-NASU							
Prof. Kolesnikov, 28	20.09.91	15.10.91	North deep part	147		51	
Mikh. Lomonosov, 54	17.11.91	03.08.92	North deep part	77	82	14	
Prof. Kolesnikov, 29	04.07.92	03.08.92	North deep part, north-west	161		81	
Mikh. Lomonosov, 55	30.09.92	05.10.92	Crimea region		48	17	
Prof. Vodyanitsky, 41	03.04.93	14.04.93	Crimea region		51	32	17
Prof. Kolesnikov, 30	04.04.93	24.04.93	North deep part	177		89	
Prof. Kolesnikov, 32	02.12.94	27.12.94	North deep part	40	134	12	
Prof. Kolesnikov, 33	16.03.95	16.04.95	North deep part	82	52	30	5
SIO-RAS							
Vityaz, 21	09.02.91	08.04.91	Central and eastern part, n.-w			26	26
Vityaz, 23	16.08.91	23.08.91	Central and eastern part, n.-w			11	11
Vityaz, 26	26.09.92	19.10.92	Central and eastern part, n.-w			14	14
Akvanavt, 6	10.10.92	15.10.92	Central part, n.-w.		48	48	
Vityaz, 27	07.11.93	15.11.93	Central part			12	12
IMS-METU							
Bilim	01.06.91	12.06.91	South part			27	
Bilim	05.09.91	23.09.91	South part			37	
Bilim	04.07.92	26.07.92	South part	144		36	
Bilim	02.04.93	14.04.93	Western part			24	4
Bilim	19.12.93	20.12.93	Near Bosphorus region	12			
Bilim	19.04.94	14.05.94	Western part	114		22	9
Bilim	18.03.95	10.04.95	Western and South part	149		4	1

measurements are done in the one - two spectral bands. The transmissometers are calibrated by the standard neutral filters. As the calibration is made in air, therefore, the correction on the difference of refraction indexes of the window and the reflector in air and in water is introduced (dc):

$$dc[m^{-1}]=1/L*Log((1-r_w)/(1-r_a))^k$$

where r_w and r_a are the coefficients of light reflection on borders of the window and reflector in water and air, k is a number of reflections of the light beam on the borders. Thus, the beam attenuation coefficient of water c_w is:

$$c_w = c_a + dc$$

where c_a is the beam attenuation coefficient obtained from the calibration in air. The main characteristics of the instruments are as follows:

- Range of measurements (by the decimal logarithm) - 0.01-1.0 m^{-1}
- Spectral interval - 360 - 700 nm
- Spectral resolution - 10 nm
- Number of spectral bands - 6 - 8
- Error of measurement of attenuation coefficient - 0.01 m^{-1}
- Error of depth measurement - 2%

Beam transmission measurements of the IMS were done using the Sea Tech Transmissometer attached to SBE CTD probe. A beam transmission T is determined by;

$$T= F_L/ F_0 .$$

The optical base of the Sea Tech Transmissometer is equal to 0.25 m. The LED is used as a light source at the 660 nm wavelength. The Sea Tech Transmissometer are calibrated by the filtered distilled water. The transmission of light with 660nm wavelength by this water over distance 0.25 m is equal to 91,3 percents. The results of measurements were given as percents of the light transmission over the distance 0.25 m. Beam transmission was converted to beam attenuation coefficient using;

$$C_{10} = 1/L\ (\log T)$$

where c_{10} is the beam attenuation coefficient with units of m^{-1}, T is transmission (%) measured by the instrument and L is the beam pathlength in m (0.25 m).

3. Long-term variability of water transparency

Time series of the horizontally averaged Secchi disk measurements from interior part of the Black Sea are given in Figure 1. Secchi disk depth had decreased slightly from 20-21 to 15-16 meters from the early 1920s to the mid-1980s. After 1985, the Black Sea water transparency has decreased dramatically and from that time Secchi disk depths were only 6-10 meters between 1990 and 1993 [1]. The central parts of the sea was occupied with waters of very low transparency (Secchi depth =2-4m) in 1992,

which were observed for the first time in the basin. It should be noted that depth of the euphotic zone was limited to upper 6-12 meters during this period.

The intense decrease in water transparency discontinued in 1992. Water transparency started to improve and by the end of 1995 the mean Secchi disk depth in the central part of the Black Sea had reached the values observed in the early 1980s, i.e. about 17 meters.

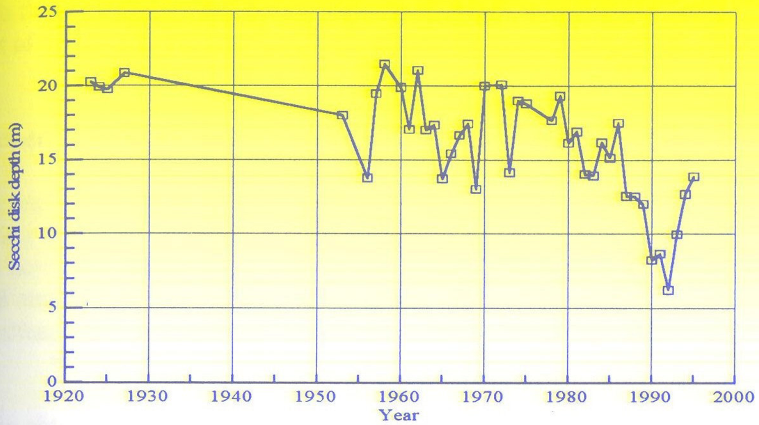

Figure 1. Long-term variability of annual mean Secchi disk depth in the central deep part of the Black Sea in 1922-1995.

Water transparency measurements using *in situ* sounding instruments were also indicating same change of transparency. Mean, maximum, minimum values and standard deviation of the beam attenuation coefficients (wavelength 410-420 nm) in the surface layer of the central deep part of the sea for summer are shown in Table 2. Values for 1977-1985 that are considered as the "background" data show large changes compared to the 1991, and 1992 data.

Spectral optical properties of the Black Sea water had also changed. Spectra of the beam attenuation coefficient c(λ) for 1984, 1991, 1992, 1995, and for the optical pure sea water are presented in Figure 2 for the subsurface water of the deep central

TABLE 2. Beam attenuation coefficients (wavelength 410-420 nm, at decimal logarithm) in the upper water layer in the central deep part of the Black Sea in summer, c(λ) $[m^{-1}]$

Year	Mean	Max.	Min	STD.
1977-1985	0.23	0.60	0.10	0.14
1991	0.45	0.94	0.30	0.09
1992	0.74	1.20	0.24	0.26

part of the sea. The Secchi disk depth values corresponding to each spectrum are given in the legend. From 1984 to 1990, the values of the light attenuation coefficient strongly increased. However, the shape of spectral curves changed, due to the initial enhanced increase in the short wavelength band. The minimum values, which were at

480 nm in 1984, shifted to 550-570 nm in 1992. This indicates significant increase of the

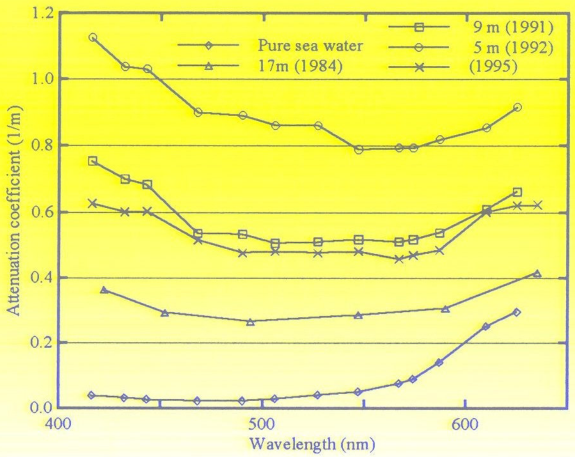

Figure 2. Spectra of the light attenuation coefficient c(λ) (natural logarithm) for the subsurface water of the deep central part of the sea for the different years and for the pure sea water. The Secchi disk depth values measured at the same station are included in a legend

"yellow substance" in Black Sea surface waters in 1991-1992.

The climatic Secchi disk depth field of the Black Sea, calculated in the years preceding the large changes of water transparency (1922-1985), and the fields of the Secchi disk depth drawn using data obtained during the surveys "Hydroblack-91" and "ComsBlack-92" are presented in Figures 3-5.

The climatic transparency field has the following features. Water with Z_d <6 m is found only in a narrow band in the regions of big river mouths as expected: Danube and Dnieper rivers on the northwest shelf, Inguri and Rioni rivers near the Caucasus, and in the vicinity of the Kerch strait. The boundary of these waters are sharply limited by the 15 isoline of salinity on the map of climatic surface salinity field for 1903-1982 in summer. In nearly 60% of the deep regions of the sea, the transparency is more than 16 m. The most transparent waters (Z_d > 22 m) occur in the middle parts of the sea where eastern and western cyclonic rings come into contacts with each other. Relatively higher transparency (up to 10-20 m) occurs in the shelf zone and often near the coast.

During Sept/Oct 1991 the range of Secchi disk values was considerably smaller than climatic values. Waters having Z_d < 6 m in 1991 was observed not only in the northwest shelf area of the basin but also down to 41°30' latitude indicating an extend of river originated turbid waters. The area of the region with this low transparency was 5 times greater compared to that in 1922-1985 period. In the earlier period, water having Z_d < 6 m was limited by the S 15 isoline, but in 1991 it was approximately S 17 . Over all the deep part of the Black Sea, values of Z_d ranged between 5-15 m. The most transparent water, with Secchi disk values 10-15 m, were observed in the eastern

part of the basin as expected. The distribution of the most transparent water was approximately the same as the distribution of the most saline surface water (S > 18).

The Secchi disk distribution in the Black Sea during July 1922 (Figure 4) was the extreme with the minimum values of the Secchi disk depth and with the most unusual distribution. The most transparent waters Z_d = 10-11 m were observed in the north-west shelf. The transparency of central deep sea region were smaller and it was only 2-10 m. The greater part of the central deep part of the eastern region was occupied with the water of very low transparency Z_d = 2-4 m, which was never observed in this part of the basin in previous years.

4. Distribution of the beam attenuation coefficient in July 1992

The measurements of vertical profiles of the beam attenuation coefficient acquired during July 1992 by the IMS and MHI were combined to display basin wide vertical and horizontal distributions. The measurements were done at different wavelengths by IMS and MHI (420 nm - MHI, and 660 nm - IMS). MHI data were recalculated to the wavelength 660 nm using;

$$C_{10}\,(660nm) = 0.127 + 0.585\, C_{10}\,(420nm)$$

to be able to combine two data sets. This formula have been obtained from spectral distribution of attenuation coefficient of the Black Sea waters.

The distribution of the beam attenuation coefficient (BAC) at 5 meters are given in Figure 6. The turbidity inferred from BAC are mostly due to small particles having diameter less than 20 µm. It has been seen that the most turbid waters were in the central part of the basin not in the coastal regions as expected. The region of minimum attenuation also matched with the low Secchi disk depth and higher temperature region. High BAC values were caused by intense phytoplankton bloom. This is the summer bloom of phytoplankton which was accelerated by the shoaling of the mixed layer. The spots with high BAC values in the southern part of the basin show patchiness of the bloom.

An example of vertical profiles of BAC and Temperature from turbid and clear waters are given in Figure 7. The turbid water was limited to mixed layer with thickness of about 15 m. The seasonal thermocline in turbid waters was sharper then in transparent waters. This shows that stability of the water column is a crucial factor in the formation of summer phytoplankton bloom in the Black Sea.

Two vertical sections of BAC , T and S at longitude 32° 15' and 36° 45' E are given in Figures 8-10. It can be seen by hydrological parameters that the spots of turbid waters coincided with zones of upwelling.

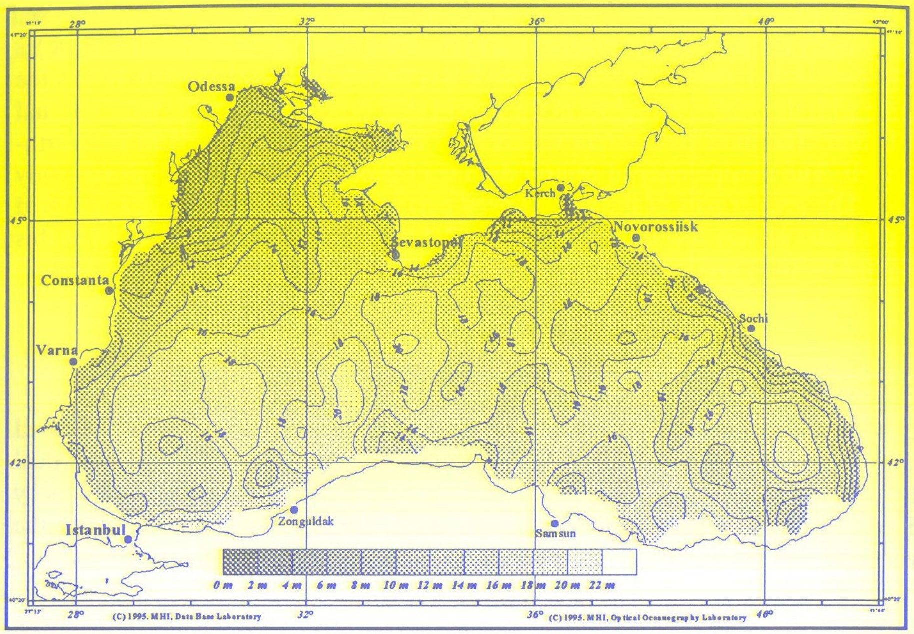

Figure 3. The climatic field of mean Secchi disk depths in the Black Sea for June - October 1922-1985.

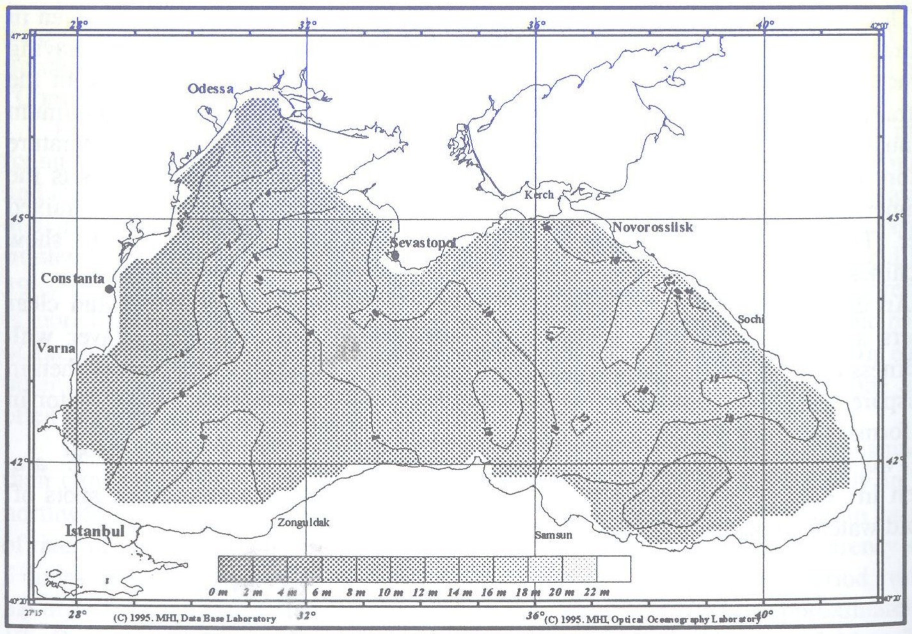

Figure 4. The distribution of Secchi disk depths in the Black Sea obtained during the HydroBlack-91 expedition in September - October 1991.

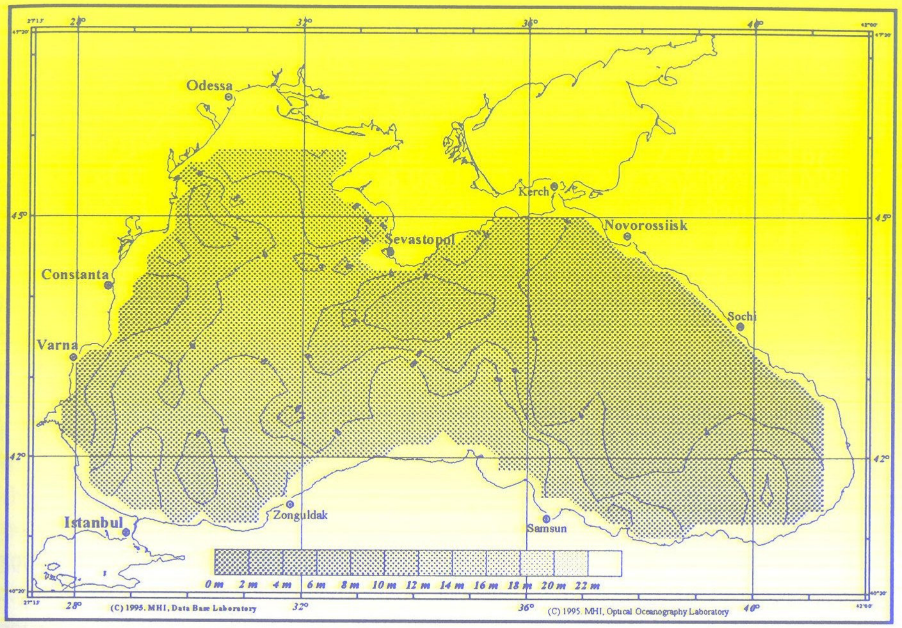

Figure 5. The distribution of Secchi disk depths in the Black Sea obtained during the CoMSBlack-92 expedition in July 1992

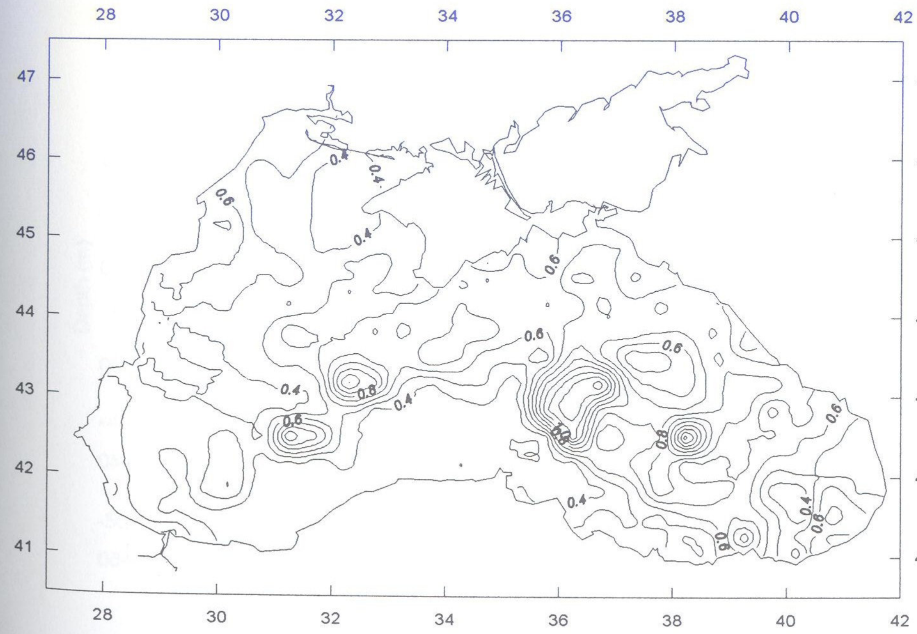

Figure 6. The distribution of the beam attenuation coefficient (660 nm, decimal logarithm) at the 5 m in July-August 1992

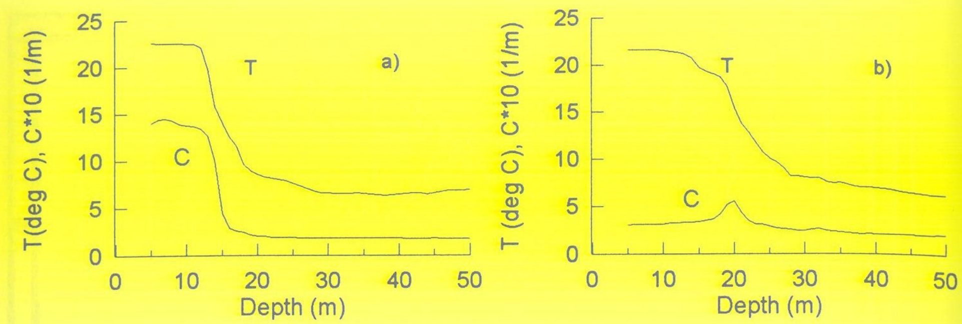

Figure 7. The vertical distribution of the beam attenuation coefficient and temperature
(a)- in the turbid water at 43 ° 10' N, 36° 45' E
(b)- in the "clear" water at 42° 30' N, 35° 15' E

5. Modeling of the optical properties of the Black Sea waters

The main cause of the very low transparency of water observed in during 1991 and 1992 cruises was the enhanced bloom of *Peridinium* and *Coccolitophores* [1]. Their content in the Black Sea waters was more than 1.5 - 2 orders of magnitude larger than in previous years and reached 2 - 3 billions per cubic meter (Figure 11). It is important to note that the major phytoplankton bloom mainly comprising *Coccolitophores* (i.e. 90 % in July 1992).

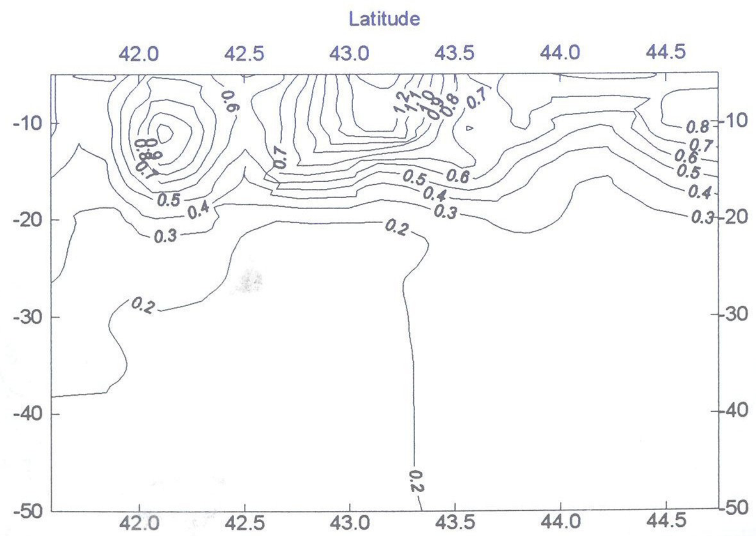

Figure 8. The distribution of the beam attenuation coefficient
(660 nm, decimal logarithm) along 36° 45' E.

Coccolitophores also play a significant role in changing water transparency, due to their crystal structure containing a number of disks, namely, coccolits, which can separated. These disks cause an intensive scattering of light. Hence, when the *Coccolitophores* concentration is high, sea water becomes whitish. This effect has been observed in the Black Sea over the last few years.

A model of the optical properties of the Black Sea water developed at MHI [1] applied to July 1992 observations to understand the abnormal changes in water transparency described above. This model allows calculations of the spectral attenuation coefficient, Secchi disk depth and spectral radiance index.

Optical properties of the clean sea water, particles, yellow substance (*gelb stoff*), phytoplankton including specific separate values for the coccolitophores were taken into account. The spectral values of the parameters used in the model were taken from a number of published sources, mostly from [4, 5, 6, 7, 8, 9] and from studies carried out at MHI.

The spectral beam attenuation coefficients obtained by the model (Figure 12) agree with the results of the laboratory and field measurements. However, it is apparent that the modeled beam attenuation coefficient doesn't show a small peak observed at 450 nm. Modelled Secchi disk depth distribution (Figure 13) using phytoplankton data collected during July 1992 cruise agree roughly with observations (cf. Figure 5). This confirms that the current phytoplankton composition and concentration can explain the observed changes of water transparency.

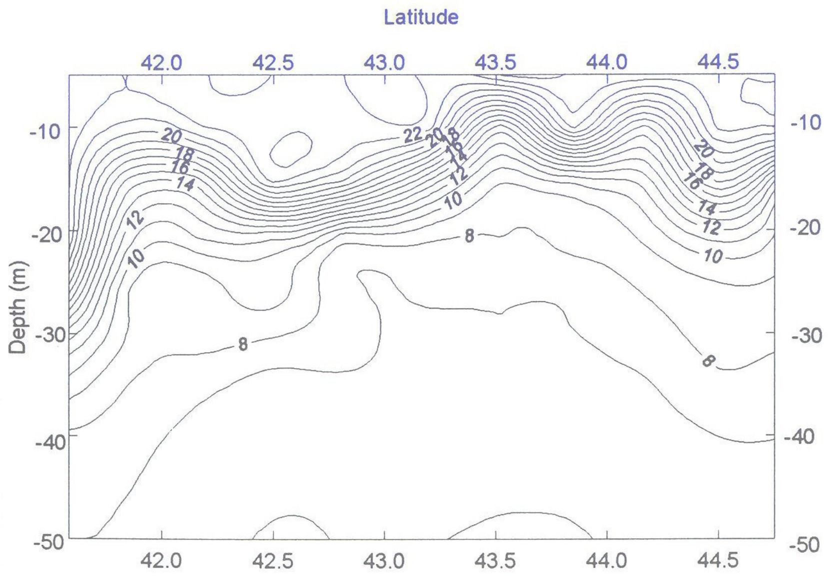

Figure 9. The distribution of temperature at section of 36°45' E.

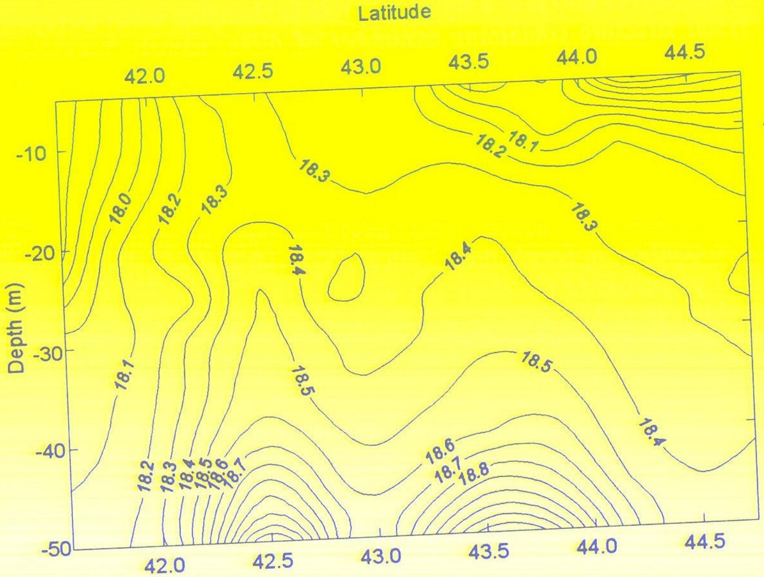

Figure 10. The distribution of salinity at section of 36° 45' E.

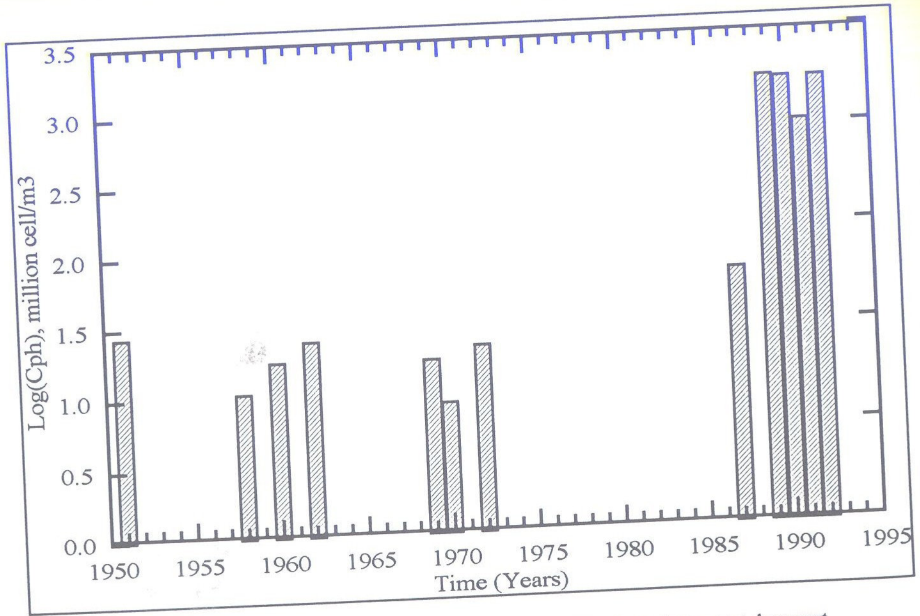

Figure 11. The phytoplankton concentration in the photic layer west deep part of the Black Sea in 1950-1992.

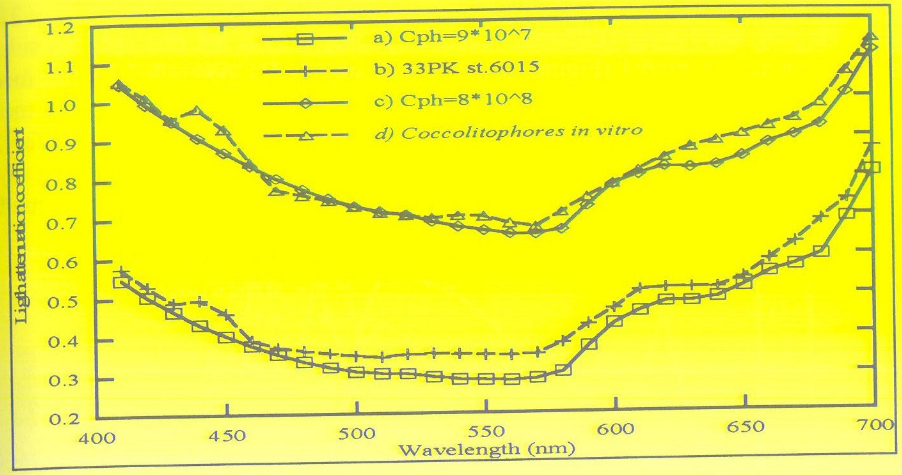

Figure 12. The measured and calculated spectral beam attenuation coefficient. The upper pair of curves: d) the measurement of the water probe contained the laboratory culture of the coccolitophores 8 10^8 cell/m^3 , c) the model function.
The under pair of curves: b) the measurement in 33 cruise "Professor Kolesnikov" (March 1995) of the water sample from the surface. The concentration of the phitoplankton in this probe was 6 10^7 cell/m^3 and 28 % its was the coccolitophores; a) the model function.

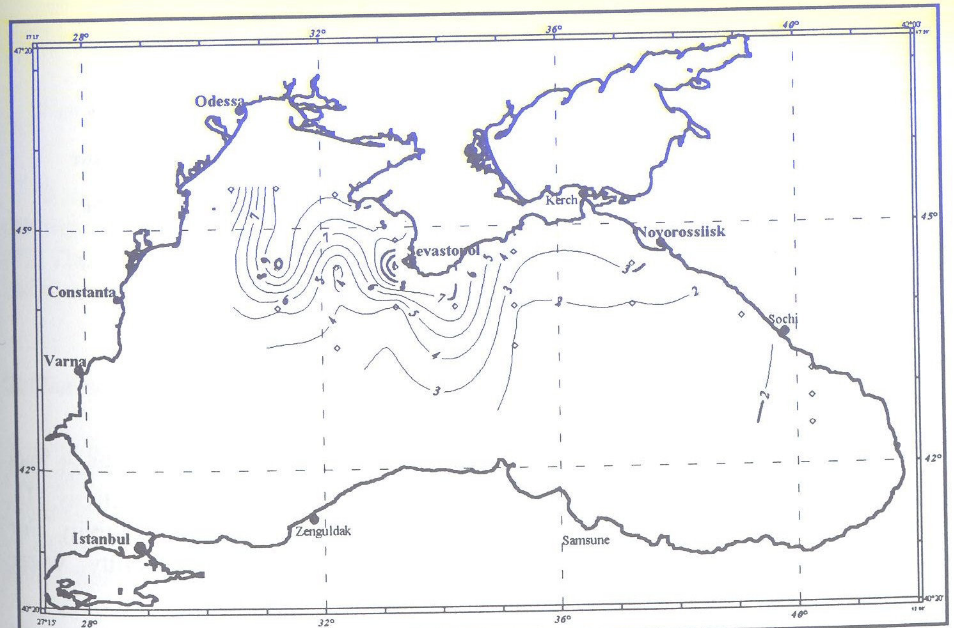

Figure 13. The distribution of the Secchi disk depth in July 1992 calculated from the optical model using the data of the plankton concentration and its composition in this time.

The influence of coccolitophores on optical properties observed during July 1992 were investigated using different coccolitophores ratios of the phytoplankton composition in the model (Figure 14). The radiance index computed by the model agrees well with the observations for Secchi disk depths to be 3-5 meters. But model computations overestimate radiance indexes at wavelengths less than 600nm for 2m Secchi disk depth. This may be due to the particulate organic matter contributing to the low values of Secchi disk observations which were not taken into account in the model.

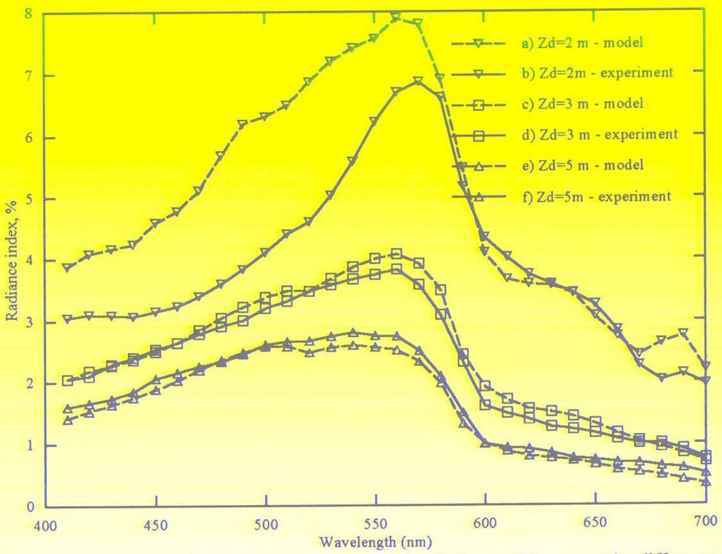

Figure 14. The measured and calculated spectral radiance indexes of the sea at the different water transparency by the Secchi disk (July-August 1992).
a) model function: the concentration of phytoplankton $C_{ph} = 1\ 10^{10}$ cell/m^3, the percentage of the coccolitophores C_{cocco} =96%; b) experiment;
c) model function: C_{ph}=3.6 10^9 cell/m^3, C_{cocco}=83%; d) experiment;
e) model function: C_{ph}=1,4 10^9 cell/m^3, C_{cocco}=62%; f) experiment

6. Periodical oscillations in long-term variability of the Black Sea water transparency

The long-term variability of water transparency (Secchi disk depth) in the Black Sea has 11 years periodicity that correlates with the 11-year cycle of solar activity [1]. There is a time lag of two years between the water transparency and solar activity. For the quasi stationary period (1953-1980) of the long-term variability water transparency, the following relation has been found;

$$\langle Z_d \rangle, \text{m} = 14.2 + 0.035 \langle N_W \rangle. \quad (2)$$

Where $\langle N_w \rangle$ is the Wolf numbers and $\langle Z_d \rangle$ is the mean Secchi disk depth.

The correlation coefficient equals $r = 0.61 \pm 0.12$ and standard deviation of the regression equals to 1.2 m. Temporal variations of water transparency measurements and the function fit using (2) are given in Figure 15.

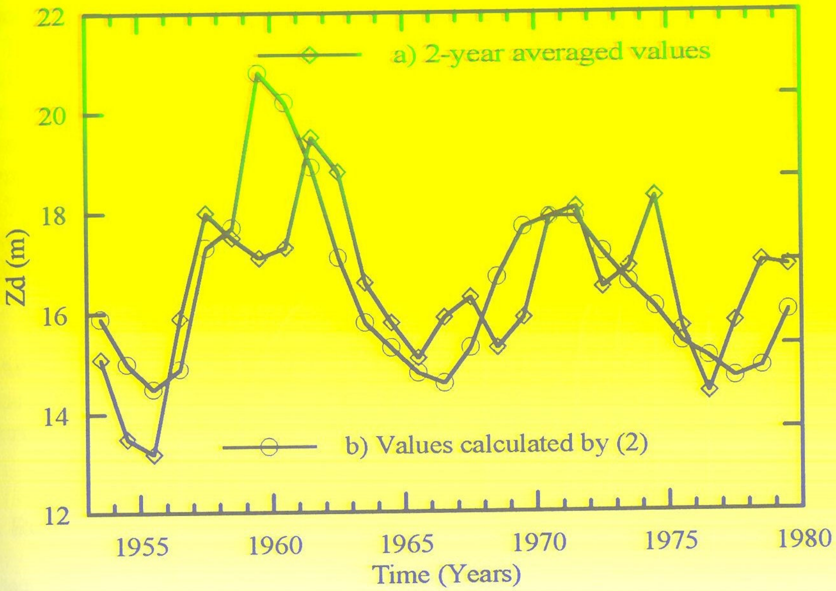

Figure 15. The time change of the solar activity in Wolf numbers (a middle for two years) and of the Secchi disk depth (a middle for two years) with the time lag equal two years.

It must be note that 11-year oscillations also exist in phytoplankton community of the Black Sea as reported for the period 1954-1990 years for the Bulgarian shelf area [2]. This was rather expected result because plankton community is the main factor influencing the variability of the water transparency.

7. The turbid boundary layer at the oxic/anoxic zone

A specific peculiarity of the vertical optical structure of the Black Sea waters is the existence of the turbid layer at the intermediate depths (Figure 16). The turbid boundary layer (TBL) is traceable over the most part of the deep section of the basin at depths of 70-210 m. The layer is most pronounced in the south-western part of the Black Sea where its value could reach 0.5-0.6 m^{-1}

There are two possible mechanism responsible for formation of this turbid layer; Bosphorus outflow [10] and chemical processes in the oxic-anoxic interface.

In [3], using the data of R/V "Knorr" cruise (May-July 1988) in the south part of the Black Sea, it was pointed out that the TBL is confined to a definite isopycnic layer, namely it is located within the layer from 15.85 to 16.31 sigma-t with an average value 16.00±0.07. We used 343 stations (without the cruise of R/V "Knorr") made in different regions of the sea in different seasons and years and found that the TBL is located at isopycnic layers from 15.34 to 16.55 with an average value 16.04 and standard deviation 0.19. Thus, there is no close connection of the position the TBL with one specific isopycnic surface, but there is some definite range of isopycnic layers where this optical layer is located.

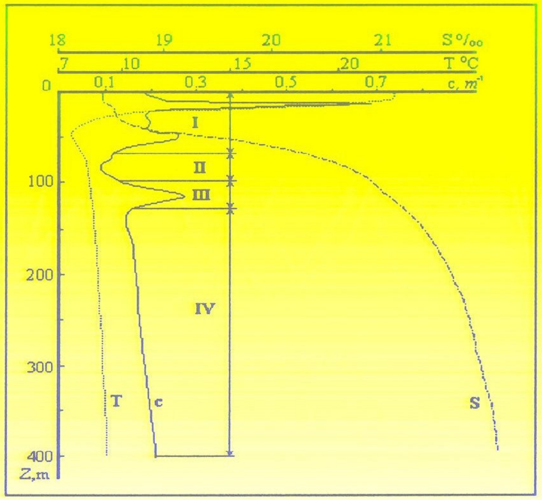

Figure 16. Typical vertical distribution of the attenuation coefficient (c), temperature (T) and salinity (S) in the deep region of the Black Sea in summer
I - the upper layer (in the photic zone) ;
II - the intermediate layer (near the low boundary of the cold intermediate layer);
III - the turbid boundary layer (in the oxic/anoxic zone);
IV - the deep layer (in the hydrogen sulfide zone).

High correlation was found between the depth of the TBL and depth of the H_2S upper boundary. For 59 stations (54 cruise of "Mikhail Lomonosov", Nov/Dec. 1991, 32 cruise of "Professor Kolesnikov", Dec. 1994) we obtained the equation:

$$Z(H_2S),\ m = 0.9\ Z(TBL) + 28 \qquad (3)$$

Coefficient correlation is r = 0.95 and standard deviation of regression is equal to 6.5 m. The depth of the H_2S onset changed in the range 105-195 m. Thus, TBL can be determined the upper boundary of the H_2S layer. It can be seen from equation (3), the deeper is the H_2S onset the less difference between the depth of H_2S zone and depth of TBL.

8. Conclusions

Observations and model studies we have presented describe the temporal and spatial variability of the Black Sea optical properties. The Black Sea surface optical properties

have well defined interannual variability with 11 years periodicity which can be related to 11 years cycle of solar activity.

The spectral optical properties of the Black Sea surface waters had remarkably changed during the last 10 years and that can be explained by increase in concentration of the yellow substance.

The agreement of the model results with observations indicate that high proportion of phytoplankton after summer bloom consists of coccolitophores. High biomass of the coccolitophores resulted in very low Secchi disk depth. Decrease in the water transparency were intensified by the strong stratification at the surface due to the summer heating.

There is a need to develop remote sensing algorithms for Black Sea for recently launched SeaWIFS ocean color data. The results of this work can be used as a background information for algorithm development and planning of the optical cruises.

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10. References

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